JOURNAL OF AIRCRAFT
Vol. 46, No. 3, May–June 2009

Engineering Notes

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Effects of Gurney Flaps on an Annular Wing

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DOI: 10.2514/1.43096

Introduction

FOR a constrained wing span, nonplanar wings exhibit significant aerodynamic benefits. These are generally indicated through increased lift curve slopes and reduced drag due to lift. These benefits are accrued through the wing capturing a larger volume of air to generate the lift impulse, and consequently the downwash at a point is reduced [1]. A simple biplane is a clear embodiment of nonplanarity. As the spacing between the upper and lower wings tends to infinity, the lift curve slope of the biplane wing tends to twice that of the equivalent monoplane, and the lift dependent drag tends to half that of the monoplane. Naturally, an infinitely spaced biplane or even that with a significant gap is not a practical design solution. As the gap between the biplane wings reduces, mutual wing interference effects reduce the nonplanar benefits. An annular (or ring) wing achieves the same aerodynamic benefits as an infinitely spaced biplane but with a maximum vertical wing spacing of the diameter of the ring. However, annular wings are hindered by their significant minimum drag coefficient that is largely due to their wetted area, which is 1.57 times greater than an equivalent projected span biplane of equal aspect ratio. Annular wings also suffer from pitch-up at stall due to dissimilar stall characteristics between the upper and lower wing halves [2]. Consequently, an active design space for annular wings is where flight operations at low speed (high loading) for extended duration are a design driver, as may be required for a small reconnaissance unmanned air vehicle [3].

Gurney flaps have received considerable attention of late as simple devices capable of augmenting the lift of a wing or airfoil [4–7]. The flap itself is usually composed of a small metal tab, typically no more then 1–2% of the chord attached perpendicular to the trailing edge on the pressure side (generally within the pressure side's boundary layer). The flaps essentially work by violating the Kutta condition at the trailing edge; thus greater loading is carried over the aft section as final pressure recovery occurs in the wake. This also has the benefit of reduced pressure recovery demands on the upper surface boundary layer [5]. The flaps have also been observed to increase base suction; beneficial in delaying stall but also causing a drag increase. Flap inclination has been indicated to be favorable in reducing drag, and placement at the trailing edge is generally indicated as being the most advantageous [5]. Segmented flaps have been studied as a means to attenuate the drag penalty of the flaps by introducing instabilities into the wake, which culminate in the breakdown of the two-dimensional vortex street that has been observed aft of the flap [6]. Lift modulation of an annular wing can be complicated due to the wing's geometric shape; flaps or ailerons may require large end gaps for clearance. Consequently, a Gurney flap may prove an effective device for force and moment modulation on an annular wing. Lift augmentation of an annular wing using Gurney flaps is apparently not documented in the literature. Consequently, a study has been undertaken to elucidate the effects of various Gurney flap configurations and layouts on the aerodynamic characteristics of an annular wing.

Equipment and Procedure

Wind tunnel tests were conducted in Embry-Riddle's 2 by 2 ft blower wind tunnel. This facility has a measured turbulence intensity of 0.5% and a jet uniformity within 1% in the jet core. Force balance measurements were undertaken using a six-component sting balance. Balance output voltages were digitized using a National Instruments 16-bit A/D board. Each presented data point is the average of 5000 readings. Before testing, the balance's calibration was checked though the application of known weights.

The model's angle of attack was set and measured using a feedback loop in conjunction with a Midori angle sensor. The angle of attack repeatability was established as better than 0.1 deg. Wall corrections were applied using the method of Shindo [8] as well as that detailed in [9]. Wind tunnel testing was conducted at a freestream velocity of 35 m/s, yielding a Reynolds number of 2×10^5 based on the reference chord c length of 0.1 m. During testing, the model was pitched to 28 deg in 2 deg increments.

The wind tunnel model was rapid prototyped from acrylonitrile butadiene styrene using Embry-Riddle's rapid prototyping facilities. The wing had a chord of 0.1 m. The model had a merged E-68 and NACA 0012 profile, and a projected aspect ratio of two . The merged section wings used the NACA 0012 profile in the last 10% of the wing tip region so that when joined, the wings had a smooth junction. Consequently, the wing possessed moderate aerodynamic washout. An image of the model and additional details may be found in [2]. The Gurney flaps were manufactured from thin brass shim and were bent to shape and attached with tape on the pressure-side trailing edge. Consequently, the flaps were composed of small segments, which were then taped over so that the flaps were continuous. Projected Gurney flap heights h of 1, 2, and nominally 3% of the chord were manufactured. Flaps orientated at 45 and 90 deg to the trailing edge were tested. The 3% 45 deg flap was measured as 2.6% high and the 90 deg flap at 3.3%. Inset sketches on the data plots elucidate the flap geometries and attachment layouts. For a given h/c, the two flap configurations had the same projected height; hence the physical length of the flaps differed.

Presented coefficients are based upon a reference area corresponding to the wing's projected area. Moments are taken about the wing's quarter chord at the center of the wing. Boundary layer transition was natural (i.e., no trip strips).

Results and Discussion

The effects of the two Gurney flap configurations and their length is explored in Fig. 1, where lift and pitching moment coefficients are

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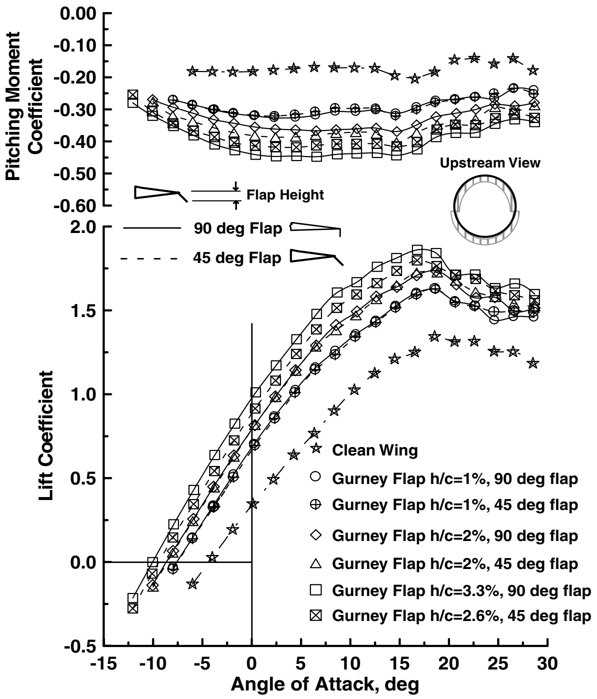

Fig. 1 Effect of Gurney flaps on measured lift and pitching moment coefficient.

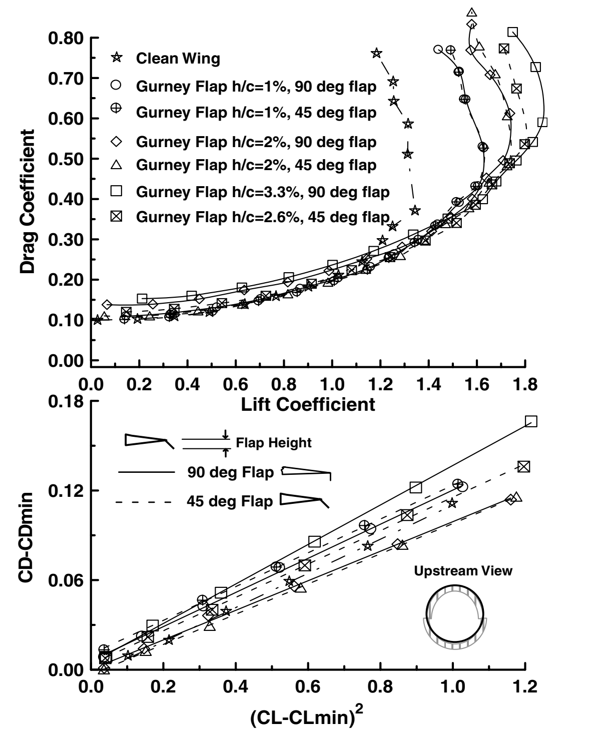

Fig. 2 Effect of Gurney flaps on measured drag coefficient and linearized drag polar, where CD is the drag coefficient and CL is the lift coefficient.

examined. The "clean wing" refers to that with no flap. The flaps were attached on the full upper- and lower-wing trailing edge extent. As is well documented, the Gurney flaps significantly increase the lift and nose-down pitching moment. This effect is accomplished in two ways: by a negative shift of the zero-lift angle of attack as well as through an increase in the wing's lift curve slope. The 1 and 2% flaps show equivalent performance for either 45 or 90 deg flap orientation, indicating that in this flap size range, the lift increment is dependent on the projected height of the flap. Within the measurement resolution, the angle of attack of stall is similar for the clean wing and that with 1 and 2% flaps. The nominally 3% flaps are indicated to stall at a lower angle of attack, which is typical for trailing-edge type flaps. The pitching moment data shows that the clean wing's aerodynamic center is approximately at the quarter chord, and flap addition moves the aerodynamic center aft, which is also concomitant with a significant increase in nose-down moment. The onset of the initial rounding of the lift curve plot (at approximately 0 deg angle of attack) for the flapped configurations is also seen to correspond to a plateau in the moment curve (moving the wing's aerodynamic center forward), suggesting that limited separation on the upper wing half has minimized any increase in the magnitude of the nose-down (a drag effect due to the location of the wing surfaces from the moment reference point) moment. Also seen in the moment curves is the break at stall. As shown in [2], this is due to large-scale separation on the upper wing (with a large drag rise), which stalls before the lower wing.

Effects of the flaps on the measured drag coefficient are presented in Fig. 2. The plot clearly shows that the 2 and 3.3% 90 deg Gurney flaps incur a significant increase in their minimum drag. This has been attributed to the flaps projecting beyond the pressure-side boundary layer; however, the 45 deg 2.6% h/c flap shows a smaller drag penalty then either of the aforementioned flaps. In this context, the 45 deg flaps may have a similar effect to segmenting the flaps, that is, breaking the two-dimensional instability in the wake (the vortex street). The slope of the linearized polars (lower inset figure) relates directly to the spanwise and sectional efficiency of the wing (as both the planform and sectional pressure drag vary with the square of the lift coefficient). As may be seen, the 2% h/c flaps appear to show the greatest efficiency.

A summary of key aerodynamic parameters is shown in Fig. 3. The Oswald efficiency factor e was calculated using the linearized polars in Fig. 3 and reflects the drag due to lift efficiency. The behavior of Gurney flaps is often cited as showing an approximately linear dependence on flap height. A recent study by Liu and Montefort [7] using thin airfoil theory suggested a lift increment dependence on $\sqrt{(h/c)}$. Consequently, the data in Fig. 3 were plotted vs h/c (not included due to space limitations) as well as $\sqrt{(h/c)}$. Identifiable dependencies were marked when presenting the data vs $\sqrt{(h/c)}$. It may be seen that the lift curve slope, maximum lift coefficient, and the zero-lift angle of attack shift show a strong correlation with $\sqrt{(h/c)}$. Although not presented, these same parameters do show an approximately linear dependency on h/c but only for $h/c \geq 1\%$.

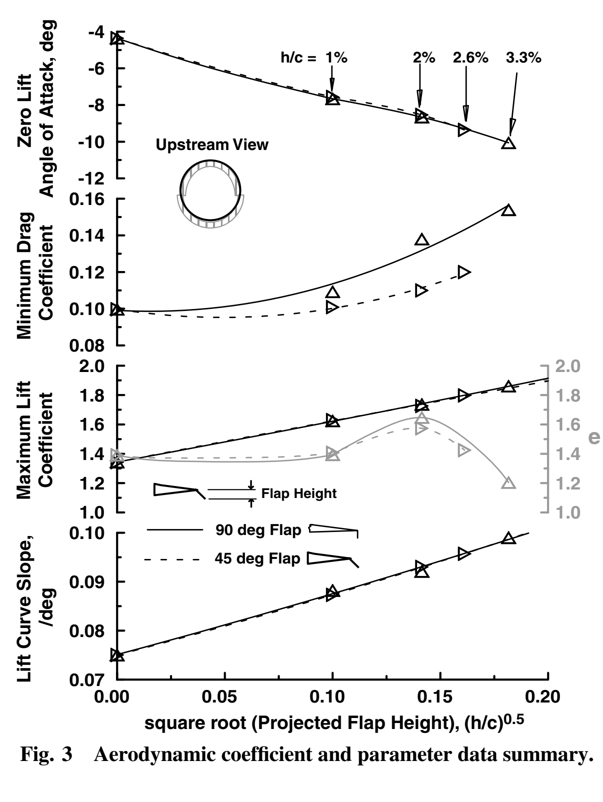

Fig. 3 Aerodynamic coefficient and parameter data summary.

There is a significant nonlinear discontinuity in going from the clean wing to 1% h/c. The collapse of the 45 and 90 deg data in all instances (except drag increment) clearly indicates that the performance of the Gurney flap is dependent on its projected height perpendicular to the attachment surface and not its physical length (for the configurations explored). Although conventional flaps commonly alter the zero-lift angle of attack, they do not typically alter the wing's lift curve slope significantly. The increase in the lift curve slope may be attributed to the increased aft loading reducing the pressure recovery demands on the boundary layer; this leads to a thinner leeward boundary layer (reduced displacement thickness) with a less effective trailing edge decambering with increasing incidence. The base suction may also delay separation resulting in a thinner boundary layer. Additionally, as suggested in [4], the thinning of the lower surface boundary layer with incidence causes an increase in effectiveness of the flap, that is, the flap is more effective at higher angles of attack and correspondingly increases the lift curve slope. Thus, the zero-lift angle of attack shift of the Gurney flap may be viewed as an inviscid effect, whereas the lift curve slope increment may be seen as a viscous behavior.

The data indicate that the total lift augmentation of the Gurney flap is due to a negative shift of the zero-lift angle of attack and an increase in the lift curve slope. Thus, the lift coefficient may be expressed as

$$C_L = (C_{L\alpha 0} + k1\sqrt{h/c})\cdot(\alpha - (\alpha_{\mathrm{ZL0}} + k2\sqrt{h/c}))$$
$$C_L = C_{L\alpha 0}(\alpha - \alpha_{\mathrm{ZL0}}) - C_{L\alpha 0}k2\sqrt{h/c} + k1\sqrt{h/c}(\alpha - \alpha_{\mathrm{ZL0}}) - k1\cdot k2(h/c) \quad (1)$$

where $k1$ and $k2$ are the gradients of the lift curve slope and zero-lift angle vs $\sqrt{(h/c)}$, as may be seen in Fig. 3. C_L and $C_{L\alpha 0}$ are the wing lift and lift curve slope (for the clean wing) coefficients. α and α_{ZL0} are the wing angle of attack and zero-lift angle for the clean wing, respectively. Consequently, the lift augmentation of a Gurney flap is dependent on both $\sqrt{(h/c)}$ and h/c. Accordingly, the rate of change of C_L with h/c varies with $1/\sqrt{h/c}$; hence the often observed linear dependence for flap heights greater than 0.75%.

The maximum recorded increase in the lift coefficient compared with the clean wing was 39% for the 3.3% 90 deg Gurney, which also indicated a lift curve slope increase of 32%. The minimum drag coefficient shows a somewhat parabolic dependence on $\sqrt{(h/c)}$. What is obvious is the greatly diminished minimum drag coefficient penalty associated with the 45 deg flap compared with the 90 deg flap. The linearized drag polar (lower inset, Fig. 2) was used to evaluate the Oswald efficiency factor, presented in gray in Fig. 3. As may be seen and was inferred in Fig. 2, the 2% flap shows the highest efficiency, with a maximum increase of 18.5% compared with the clean wing.

Figure 4 presents the effect of asymmetric flap attachment. Various configurations were explored to determine the effect of flaps on the upper and lower wings, as well as a configuration designed to generate a yawing moment and side force (demarcated by a *Y* legend symbol). The selected flap geometry was the 2% flap at 45 deg. As may be seen, the lift coefficient for flap attachment on either the upper or lower surface falls approximately midway between the clean wing and that of flap attachment on both the upper and lower wing section. This suggests approximately equal loading on the wing sections. However, the pitching moment characteristics are different for these two configurations due to the disparate drag when the flap is attached. Attachment on the upper surface shows a reduced nose-down moment compared with attachment on the lower wing half, due to the increased profile drag (and increased vortex drag resulting from greater loading) of the upper wing half. An interesting result is indicated for the side force configuration showing a significant delay in the onset of stall, in conjunction with the generation of significant side force and yawing moment. Notice that the pitch-up of the side force (Y) configuration wing is greatly attenuated compared with the other wings, suggesting a delay in the onset and progression of stall of the upper wing half. It may be that the stall delay is due to the asymmetric spanwise load distribution reducing the spanwise flow

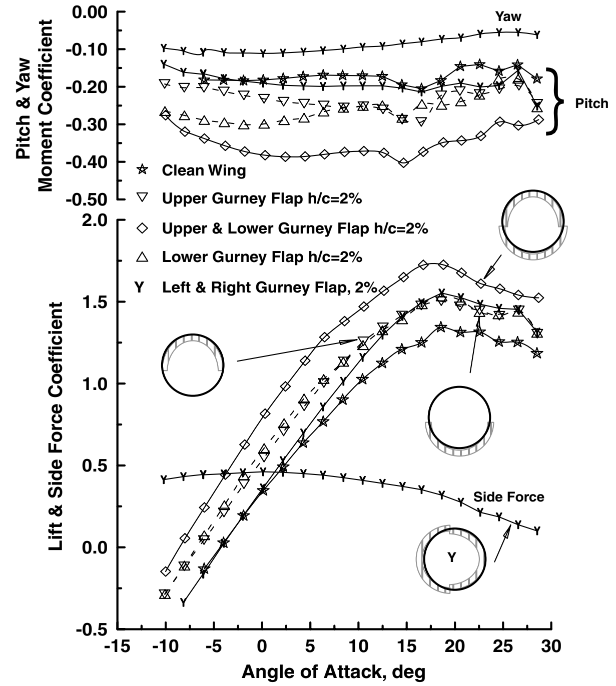

Fig. 4 Effect of asymmetric Gurney flap attachment on measured forces and moments. Flap configuration; 2% flap at 45 deg.

toward the top of the upper wing half, so by delaying stall of the upper wing section and slowing the forward progression of the separation point (i.e., the observed stall mechanism for this wing [2]). It was also validated experimentally (not shown) that a ring wing is incapable of generating a significant rolling moment, as all pressure-induced loading acts through the center of the ring.

Conclusions

An experimental investigation has been conducted to determine the effects of Gurney flaps on an AR $= 2$ annular wing. Tests were undertaken at $Re = 2 \times 10^5$. Different flap geometries and placements were investigated. The results indicated that the flaps significantly increased the wing's maximum lift coefficient and lift curve slope. Inclined flaps were shown to offer superior efficiency for similar levels of lift augmentation. The lift curve slope, angle of attack for zero lift, and the maximum lift coefficient exhibited a dependency that scaled with the square root of the flap's projected height. The projected height of the flap was seen to determine the aerodynamic characteristics.

Acknowledgments

The author would like to sincerely thank Samantha Seagren, Robert Wilson, Adam Wolfe, Brian Beasley, and Jun Ko for the design and assembly of the flaps as well as undertaking the wind tunnel testing. The author would also like to thank the Associate Editor and reviewer for their useful comments and suggestions.

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